Accounting for Temperature Effects on the Performance of Soil Moisture Sensors in Sandy Soils

Michelle Schwartz*
Dep. of Civil Engineering
Univ. of Texas at Arlington
Nedderman Hall 417
416 Yates Street
Arlington, TX 76010

Zhen Li
Dep. of Civil and Environmental Engineering
Colorado School of Mines
Golden, CO 80401

Toshihiro Sakaki
Dep. of Civil and Earth Resources Engineering
Kyoto Univ.
Kyoto, 606-8501, Japan

Ali Moradi
Dep. of Environmental Resource Engineering
Humboldt State Univ.
Arcata, CA 95521

Kathleen Smits
Dep. of Civil Engineering
Univ. of Texas at Arlington
Nedderman Hall 417
416 Yates Street
Arlington, TX 76010

Core Ideas

• Two-point α-mixing model with modified α-value improves ambient calibration for 5TM.

• Sensor’s temperature response can be predicted as a function of water content.

• Linear trend is adequate for predicting sensor’s temperature response.

Capacitance sensors are widely used to monitor volumetric water content in both field and lab settings due to their low cost, ease of use, and capability of providing continuous measurements. However, these sensors are sensitive to temperature variations. Previous attempts to develop calibration equations that negate thermal effects incorporate many empirical constants that vary based on soil and sensor type. The purpose of this study is to examine the effects of temperature on sensor performance and develop an improved calibration equation for a widely used capacitance soil moisture/temperature sensor, the ECH2O 5TM. Small cell experiments were conducted with silica sands for a range of temperatures (20–50°C) and water contents. The 5TM showed a bi-directional response to temperature increases based on the soil water content. Within the temperature range examined, the slope of sensor-reading vs. temperature could be predicted using a linear relationship as a function of actual water content.

Abbreviations: TDR, time domain reflectometry.

Measurement of soil moisture under varying temperature conditions is important to many applications, ranging from hydrologic modeling (Assouline et al., 2010) to irrigation in agriculture (Sui et al., 2012; Sharma et al., 2017). Capacitance sensors, which are often used to monitor soil moisture in both field and lab experiments, determine volumetric water content (θ) in soil with an electromagnetic field to measure the capacitance of the bulk soil using an oscillator (Parvin and Degre, 2016). However, soil temperature significantly affects capacitance sensor readings, with temperature effects ranging from 0.002 m³ m⁻³ °C⁻¹ to 0.005 m³ m⁻³ °C⁻¹ (e.g., Wraith and Or, 1999; Campbell, 2006; Cobos and Campbell, 2007; Kizito et al., 2008; Saito et al., 2009; Assouline et al., 2010; Fares et al., 2016), and widely used calibration methods fail to account for these temperature effects.

The calibration of dielectric sensors is commonly based on the empirically derived equation from Topp et al. (1980), which relates a sensor-measured dielectric permittivity (ε_meas) to θ:

\[ \theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} \varepsilon_{\text{meas}} - 5.5 \times 10^{-4} \varepsilon_{\text{meas}}^2 + 4.3 \times 10^{-6} \varepsilon_{\text{meas}}^3 \]  

[1]

Equation [1] was specifically developed in a controlled lab environment at ambient temperatures (20°C) for time-domain reflectometry (TDR) techniques applied to mineral soils (Topp et al., 1980). Evett and Parkin (2005) point out that Eq. [1], although useful in select applications, is limited to the soil properties, site conditions, and sensor characteristics in which the sensor is tested.

Another method to calibrate capacitance sensors is with a mixing model. Based on the commonly used four-phase dielectric mixing model (Dobson et al., 1985), Sakaki et al. (2008, 2011) developed a simplified two-point α-mixing mod-

doi:10.2136/sssaj2019.05.0161
Received 24 May 2019.
Accepted 30 July 2019.
*Corresponding author (michelle.schwartz3@mavs.uta.edu).
© Soil Science Society of America. This is an open access article distributed under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)
el for several ECH$_2$O capacitance sensors (Meter Group, Inc., Pullman, WA):

$$\theta = \frac{\text{RAW}_{\text{sat}} - \text{RAW}_{\text{dry}}}{\text{RAW}_{\text{sat}} - \text{RAW}_{\text{dry}}} \phi$$

where $\phi$ is the soil porosity; RAW$_{\text{sat}}$ is the raw sensor output; RAW$_{\text{sat}}$ and RAW$_{\text{dry}}$ are the raw sensor values obtained at full and air-dried saturations, respectively; and $\alpha$ is an empirically determined sensor type-specific geometric parameter. This model only requires knowledge of two extreme values to calibrate a soil sample: the RAW$_{\text{sat}}$ and RAW$_{\text{dry}}$ values. When compared to other calibration methods, such as developing a quadratic curve to define the relationship between RAW and $\theta$, the two-point $\alpha$-mixing model was found to be accurate and simple (Sakaki et al., 2008). Sakaki et al. (2011) briefly examined the EC-5 (one of the above-mentioned ECH$_2$O capacitance sensors) sensor response to $20^\circ$C. Sakaki et al. (2011) briefly examined the EC-5 (one of the above-mentioned ECH$_2$O capacitance sensors) sensor response to $20^\circ$C, but it is unknown if this result will be observed with other capacitance sensors.

There have been recent attempts to develop calibration equations for capacitance sensors that account for thermal effects. Saito et al. (2009) and Fares et al. (2016) developed a relationship between the sensor-measured soil volumetric water content and temperature when the actual water content was held constant. Similarly, Schwartz et al. (2009a, 2009b) developed a calibration method using TDR sensors in clayey soils under varying temperature conditions based on specific surface area and the apparent electrical conductivity. Both Saito et al. (2009) and Fares et al. (2016) observed a linear trend for sensor readings when temperature varied between 5 and 35$^\circ$C or 1 and 45$^\circ$C, respectively, where the magnitude and sign of the slope was dependent on the actual water content of the system. Each developed an equation for calculating the actual water content from sensor and temperature measurements. However, the relationships found by Saito et al. (2009) and Fares et al. (2016) between temperature and sensor readings are highly dependent on empirical constants being calibrated for each combination of soil and sensor type.

For applications involving shallow subsurface moisture dynamics where temperature and moisture can fluctuate significantly (i.e., land-atmosphere interactions), the ECH$_2$O 5TM (Meter Group, Inc., Pullman, WA) is a commonly used volumetric water content sensor. The 5TM sensor is capable of making simultaneous temperature and volumetric water content measurements, making the sensor better suited for environments with high temperature fluctuations than other sensors (e.g., the EC-5). Therefore, 5TM sensors were used in this study and were determined to require a more detailed calibration with temperature effects. The main objectives of this study are to develop (1) an improved calibration equation at room temperature and (2) a temperature calibration equation for the 5TM sensors in silica sands.

**MATERIALS AND METHODS**

**Sensor Properties**

The 5TM sensor is a three-prong sensor (10 cm by 3.2 cm by 0.7 cm) with a thermistor underneath the sensor overmold. Two prongs are for capacitance measurement: the outer one being the plus prong (dominant). The capacitance is measured using the charge/discharge time using an oscillator supplying a square wave signal at 70 MHz. The third prong is for temperature measurement, and is in direct contact with the internal thermistor. This sensor has a maximum possible sampling volume of 715 cm$^3$ around the sensor in the shape of an ellipsoidal cylinder that extends past the prongs by 1 cm, 5 cm perpendicular to the flat side of the prongs, and 4.75 cm perpendicular from the top of the sensor (Meter Group, Inc., 2017). Raw 5TM sensor outputs are reported as 50°C when connected in standard serial communication.

**Soil Properties**

Three types of silica sand were used in this study. Two silica sands are identified by their effective sieve numbers as #30/40 and #50/70 Accusand (Unimin Corporation, Ottawa, MN), and F110 Ottawa foundry sand (US Silica, Ottawa, IL) (hereafter referred to as #110 sand) was used as a finer-grained sand. Silica sands were chosen for this experiment because they have been well-studied and characterized. These sands exhibit a narrow range in particle size distribution which minimizes variability. The sands are mostly composed of silica dioxide (Unimin Corporation, 2014) and do not experience changes in dielectric permittivity with the change in temperature examined in this study. For more information on the physical and hydraulic properties of the sands used in this experiment, the reader is referred to Deepagoda et al. (2016) and Sakaki and Illangasekare (2007).

**Experimental Setup**

A clear-cast acrylic tube (I.D. = 12.7 cm, O.D. = 13.97 cm, height = 15 cm, internal volume ~1,900 cm$^3$) was instrumented with one 5TM sensor installed at a depth of 6.35 cm so that the entire measurement volume was contained within the soil. According to the maximum sampling volume defined by Meter Group, Inc. (2017), the total measurement depth of the 5TM sensor is approximately 7.75 cm, which is slightly over half of the depth of the experimental cell. The output of the sensor is the average volumetric water content across the whole measurement depth. The sensor was installed using through-fittings. For all trials, the 5TM sensor was oriented horizontally within the cell with the plus prong located at the top of the sensor. The sensor was interfaced with an ECH$_2$O Em50 Data Logger (excitation voltage = 3V). Soil volumetric water content and temperature measurements were collected every 2 min during the duration of each trial.

Each soil sample was packed to a predetermined volumetric water content. In total, twelve volumetric water contents were used in this study to get a wide range of conditions. For each sample, a known volume of deionized water was added to a known mass of oven-dried soil, which was mixed thoroughly to create a homogeneous mixture with the designated volumetric water content. The experimental small cells were uniformly packed with the sand-water mixture in layers of 3 cm to a specified porosity of 0.324.

After packing, the cell was immediately covered with plastic wrap to avoid evaporation and placed within an incubator.
(Fisher Scientific Isotemp 650D) set to 20°C and allowed to stabilize for approximately 2 h. The temperature of the incubator was then raised from 20 to 50°C using increments of 5°C every 2 h, which was sufficient for the soil temperature to equilibrate with the incubator temperature.

**Model Development and Analysis**

The room-temperature calibration of the 5TM sensor was developed using the 5TM’s RAW readings at room temperature (i.e., 23 ± 2°C) from each trial. The RAW values from the STM sensor were input into Eq. [2] (two-point α-mixing model) with a variable α. The resulting 5TM readings were compared to the initial water content to which the cell was packed (θ_p). The α-value was determined using the least-squares method.

Temperature calibrations were based off of the findings of Saito et al. (2009) and Fares et al. (2016). The overall equation was derived from the relationship:

\[
\frac{dθ_i}{dT} = f(θ_i) \quad [3]
\]

where \( \theta_i \) is the sensor reading calculated with the two-point α-mixing model; \( \theta_i \) is the actual water content; \( T \) is the system temperature (°C); and \( f(θ_i) \) is a fitted function, often quadratic or cubic, that represents the slope of the \( \theta_i \) and \( T \) relationship. The equation is then integrated to yield:

\[
θ_{i,s} = θ_p + f(θ_i)(T − T_r) \quad [4]
\]

where \( θ_{i,s} \) represents the sensor-read volumetric water content at a reference temperature; and \( T_r \) is the reference temperature (i.e., room temperature).

In practical application, the sensor measurement \( θ_i \) and the corresponding temperature \( T \) are available from the 5TM readings, and the actual water content \( θ_p \) is unknown. To determine the unknown \( θ_p \), it is necessary to express both \( θ_{i,s} \) and \( f(θ_i) \) as a function of \( θ_p \). For \( θ_{i,s} \), the function with respect to \( θ_p \) can be determined by developing a relationship between sensor-read volumetric water contents at room temperature, \( θ_p (23 \pm 2°C) \), and the packed water content, \( θ_p \), which is assumed to equal \( θ_p \). Fares et al. (2016) argues that \( θ_{i,s} \) and \( θ_p \) are equal when a soil-specific calibration equation is used; sensor readings at specified temperatures for calibration should equal the actual water content of the soil without any correction factors if an appropriate soil-specific calibration equation is used.

The equation for \( f(θ_i) \) is determined using Eq. [3]. Sensor readings, calibrated using the two-point α-mixing model with the modified α-value, were plotted against temperature to determine the linear trend. The slope of the trend line for each water content trial, \( dθ_i/dT \), was plotted with the respective \( θ_{i,s} \), which was assumed to equal \( θ_p \). The relationship between \( θ_i \) and the slope of the temperature effect on sensor reading was defined three different ways to determine which best represented the observed trend: a linear relationship, a quadratic relationship (as proposed by Saito et al., 2009), and a cubic relationship (as proposed by Fares et al., 2016). The general equation, using the unknown variable \( θ_p \), is shown in Eq. [5]:

\[
f(θ_i) = a_0 + a_1θ_i + a_2θ_i^2 + a_3θ_i^3 \quad [5]
\]

where \( a_0 \) to \( a_3 \) are empirical constants calculated for each combination of soil and sensor type.

A linear relationship, \( f(θ_i) \), was predicted to be representative of the slope and water content relationship for silica sands, as previous studies on temperature effects on ECH2O sensors in sand showed an approximately linear relationship between \( dθ_i/dT \) and \( θ_p \) (e.g., Kizito et al., 2008; Saito et al., 2009) even though authors chose a higher-order relationship to characterize more types of soil (e.g., Saito et al., 2009). The calibration equation, referred to as the modified α-mixing model, which can be used for the ECH2O 5TM sensor that negates the effect of temperature, can be defined as follows:

\[
\frac{RAW_{w,s} - RAW_{w,0}}{RAW_{w,v} - RAW_{w,0}} = a_0 + a_1(T - T_r) \quad [6]
\]

where \( a_0 \) and \( a_1 \) are the empirical constants developed from soil-specific calibrations. The RAW_{w,s} and RAW_{w,0} values can be obtained from testing soils in air-dry and fully saturated conditions, and the α-value is held constant. The equation can be rearranged to solve for the actual water content \( θ_p \):

\[
θ_p = \frac{RAW_{w,s} - RAW_{w,0}}{RAW_{w,v} - RAW_{w,0}} (T - T_r) \quad [7]
\]

The modified two-point α-mixing model was analyzed for different silica sands to determine its efficacy.

**RESULTS AND DISCUSSION**

**Experimental Results under Room Temperature Conditions**

Figure 1 shows the sensor-measured volumetric water contents for the two-point α-mixing model (using RAW sensor output) and the Top et al. (1980) equation (using dielectric permittivity output; 1/50 × RAW) compared to the packed water contents. It can be seen that using a best-fit α-value, the two-point α-mixing model produced a better fit with the actual water content than the manufacturer-specified Top et al. (1980) equation for all studied grain sizes. By using a best-fit α-value of 0.254, which was consistent across all three grain sizes, the two-point α-mixing model produced better sensor-measured values for extreme levels of saturation (Fig. 1a). This difference in calibration equations is reflected in their respective \( R^2 \) values; the two-point α-mixing model produced an \( R^2 \) value of 0.983 while the Top et al. (1980) equation produced an \( R^2 \) of 0.942.

**Temperature-Dependent Calibration**

Although not shown, the sensor readings displayed a linear relationship with temperature. The value of the slope of the sensor reading with temperature was dependent on the measured soil water content, \( θ_p \); soils with lower volumetric water contents exhibited a positive \( dθ_i/dT \) while soils with high volumetric water contents exhibited a negative \( dθ_i/dT \) with increasing temperature. To determine if water redistribution played a major role in the observed relation-
ship, gravimetric water content analysis was conducted near the sensor and compared with \( q_p \) after each water content trial. The average difference between initial packed water content and final gravimetric water content analysis was between 0.001 to 0.0136 m\(^3\) m\(^{-3}\). It is thus fair to assume that the redistribution of water in the cell had little to no influence on the results of this experiment.

The behavior of capacitance sensors in silica sands in this study is consistent with the findings in Saito et al. (2009) for the EC-10 in Tottori sand and Fares et al. (2007) for a multisensory capacitance probe in quartz sand. Interestingly, this differs from temperature-dependent TDR measurements in sandy soils, as illustrated by Wrath and Or (1999) and Schwartz et al. (2009a), where both report a consistently negative \( d q_s / dT \) across all water contents in sandy soils. This difference can likely be attributed to the different permittivity measurement techniques for the capacitance sensors and TDR sensors (Kelleners et al., 2005) and factors that may differently affect such measurements when exposed to varying temperatures. Further investigation into why these dielectric sensors respond differently to temperature changes in sandy soils is recommended.

The slope of the temperature effect on sensor readings for each water content trial was plotted against the respective \( q_p \) value to develop the \( f(q_a) \) equation, as shown in Fig. 2. Table 1 shows the equations and their respective \( R^2 \) values. As the results indicate, increasing the number of variables in the \( f(q_a) \) equation does not significantly increase the \( R^2 \) value. This implies that a linear relationship between \( d q_s / dT \) and \( q_p \) performs nearly as well as a quadratic function, as proposed by Saito et al. (2009), or a cubic function, as proposed by Fares et al. (2016), for a silica sand. Using a linear relationship also reduces the number of empirical constants to be derived for the temperature calibration.

The resulting slope and intercept for the \#50/70 and \#110 sands’ linear \( f(q_a) \) were very similar as shown in Table 1. This consistency can likely be attributed to the similar material properties of both of the sands; both sands are natural silica sands sieved to a specific effective mesh size. It is unknown if the calibration equation derived for silica sands is applicable to all effective sizes of manufactured silica sands, and further testing is necessary to determine if the empirical constants can be held constant for all silica sands.

The error bars that were applied to \( d q_s / dT \) were determined from the standard error of the measured \( d q_s / dT \) from the \( f(q_a) \) trendline for each sand grain size. The error bar sizes for these experiments were determined to be ±0.00017 for the \#50/70 sand and ±0.00013 for the \#110 sand. Error could have come from multiple aspects of this experiment: heterogeneity induced during layer-wise packing of cells and sensor sensitivity being chief among them. Nonetheless, the above-mentioned linear relationship was still significant.

Based on the findings from the room-temperature and temperature-dependent analysis, the modified two-point \( \alpha \)-mixing model (Eq. [7]) can be used to correct the effects of temperature on sensor readings in silica sands. The effect of temperature on sensor readings could be predicted by a linear \( f(q_a) \). The empirical parameters \( a_0 \) and \( a_1 \) varied based on sand grain size, while the parameter \( \alpha \) remained constant at 0.254 for all sand grain sizes tested.

**CONCLUSION**

In this study, focus was placed on establishing a calibration equation for the relatively low-cost capacitance soil moisture/tem-
perature sensor ECH2O 5TM with effects of temperature changes. The calibration of the ECH2O 5TM volumetric water content and temperature sensor for both room temperature and temperature-dependent experiments yielded an equation with a total of three empirically derived constants dependent on soil and sensor type: one for the α-mixing model and two for incorporating the effects of temperature changes into the calibration. For room temperature calibrations of sands, the two-point α-mixing model (Eq. [2]) with an α-value of 0.254 yielded improved results compared to the manufacturer-recommended Topp et al. (1980) calibration equation (Eq. [1]), which over predicted volumetric water contents at extremely low and extremely high levels of saturation.

The relationship between 5TM sensor readings and temperature for silica sands was linear with the slope dependent on the actual water content. Sensors in samples with high volumetric water contents at high temperature underpredicted water contents while sensors in low volumetric water contents at high temperatures overpredicted water content. The findings of this study are consistent with previous bi-directional temperature responses in sands for capacitance sensors (e.g., Fares et al., 2007; Saito et al., 2009). However, these temperature responses differed from temperature responses with TDR sensors, which exhibit negative slopes regardless of water content. The slope of temperature-sensor relationship, \( \frac{dT}{dQ} \), could be predicted by a linear function with respect to the actual water content, \( f(Q) \), for silica sands. Higher-order \( f(Q) \) equations could be used to predict \( \frac{dT}{dQ} \) based on \( Q \), but these equations minimally impacted the \( R^2 \) value of the model. The linear \( f(Q) \) requires only two empirical parameters, reducing the number of empirical parameters needed. Further experimentation with different sizes of silica sands is necessary to determine if \( a_0 \) and \( a_1 \) values can be held constant for this particular type of soil.

**ACKNOWLEDGMENTS**

This research was funded by the National Science Foundation Project Award No. 1447533. The support from the Edna Bailey Sussman Foundation and the Phillips 66 Research Experience for Undergraduates—Environmental Engineering is also acknowledged for their contributions to the project. The authors would like to thank the editor and the anonymous reviewers for their time and consideration.

**REFERENCES**


<table>
<thead>
<tr>
<th>Relationship</th>
<th>#50/70 Sand</th>
<th>#110 Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linearity 0</td>
<td>4.9×10⁻⁴</td>
<td>4.2×10⁻⁴</td>
</tr>
<tr>
<td>Linearity 1</td>
<td>2.7×10⁻³</td>
<td>2.9×10⁻³</td>
</tr>
<tr>
<td>Linearity 2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>R²</td>
<td>0.7388</td>
<td>0.8456</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Relationship</th>
<th>#50/70 Sand</th>
<th>#110 Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadratic 0</td>
<td>4.9×10⁻⁴</td>
<td>4.9×10⁻⁴</td>
</tr>
<tr>
<td>Quadratic 1</td>
<td>2.7×10⁻³</td>
<td>4.7×10⁻³</td>
</tr>
<tr>
<td>Quadratic 2</td>
<td>1.6×10⁻²</td>
<td>5.7×10⁻³</td>
</tr>
<tr>
<td>R²</td>
<td>0.7389</td>
<td>0.8725</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Relationship</th>
<th>#50/70 Sand</th>
<th>#110 Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cubic 0</td>
<td>5.2×10⁻⁴</td>
<td>4.7×10⁻⁴</td>
</tr>
<tr>
<td>Cubic 1</td>
<td>2.4×10⁻³</td>
<td>3.8×10⁻³</td>
</tr>
<tr>
<td>Cubic 2</td>
<td>1.6×10⁻²</td>
<td>2.5×10⁻³</td>
</tr>
<tr>
<td>R²</td>
<td>0.7457</td>
<td>0.8740</td>
</tr>
</tbody>
</table>

Table 1. Comparison of trend lines and R² values for both #50/70 and #110 sand; a₀ to a₃ are empirical constants calculated for each combination of soil and sensor type.